The Australian Journal of Agricultural and Resource Economics, 45:2, pp. 233–256

An economic analysis of farm forestry as a means of controlling dryland salinity†

Oscar Cacho, Romy Greiner and Lachlan Fulloon*

Large areas of agricultural land under conventional crops and pastures are at risk of dryland salinisation in Australia. The salinisation problem can be controlled by strategic and large-scale planting of trees; however, farm forestry enterprises evaluated with conventional discounting techniques do not generally rank as an attractive alternative to annual crops on productive land. In this article, an optimal control model that explicitly accounts for decline or improvement in land quality over a period of 40 years is presented. The optimal area planted to trees and the optimal groundwater-table trajectory through time are determined under a variety of scenarios. Implications of the results for policy design are discussed.

1. Introduction

Dryland salinisation is a serious land degradation problem that affects many regions across Australia. The estimated area of land affected by dryland salinity rose from 0.4 million hectares in 1982 to 1.2 million hectares in 1993 (Robertson 1995). Up to 15 million hectares may become salt-affected unless substantial changes to current land-use systems are implemented (Martin and Metcalfe 1998). The recently released salinity audit of the Murray–Darling Basin (Murray–Darling Basin Ministerial Council 1999) estimates the cost of salinity in the Basin at A$46 million a year. This estimate, which includes the cost caused by saline river water and rising water tables in both agricultural and urban areas, is expected to rise further. The audit estimates that in some areas of the Basin (such as the Macquarie, Namoi and Bogan Rivers) the average salinity will exceed the threshold for drinking water quality in 20 years.

---

† The authors are grateful to two anonymous referees for many valuable comments on earlier drafts of this manuscript and to John Dillon who provided a number of useful suggestions.

* Oscar Cacho and Lachlan Fulloon, Graduate School of Agricultural and Resource Economics, University of New England, Armidale, NSW 2351. Romy Greiner, CSIRO, Tropical Agriculture, Davies Laboratory, PMB Townsville QLD 4814. Part of this work was completed by Cacho while on study leave with the Agricultural and Resource Economics group at the University of Western Australia.

The technical reasons for the emergence of dryland salinity are well known; as deep-rooted native vegetation is replaced with European-style cropping and grazing systems, which use less water, a larger proportion of rainfall recharges the groundwater systems resulting in rising groundwater tables. In the process, salts from the bedrock are mobilised and brought to the land surface, resulting in salinisation of land and surface water. Plant growth on saline soils is impaired through various chemical effects (Greiner 1997). Conventional annual crops are particularly salt-sensitive and land affected by soil salinity may eventually become unusable for their production. On-farm costs resulting from salinity include profitability loss and infrastructure damage (Dryland Salinity Management Working Group 1993). Off-site costs to downstream industries, governments and the community at large are substantial (Oliver *et al.* 1996).

Lack of knowledge has been a key factor contributing to the emergence of salinity. However, despite increasing evidence on the nature and extent of salinity, control effort remains sketchy. Quiggin (1987) sees the key behavioural and economic causes in terms of a continued lack of site-specific understanding, the current property rights situation of groundwater systems as open access resources, and short-term decision-making by farmers associated with high discount rates.

Arguably, control of dryland salinisation of agricultural land will have to be based on biological methods as engineering techniques[1] are too costly to implement at the required scale and, as pointed out by Quiggin (1986), engineering solutions would only reduce costs of dryland salinity to farmers and send the wrong signal. Agronomists have shown that deep-rooted perennial crops and trees are characterised by high and year-round transpiration. There is empirical evidence that trees can provide an effective biological tool for controlling groundwater tables and dryland salinisation, e.g., Davidson (1993), Farrington and Salama (1996), Schofield (1992), Stolte *et al.* (1997). There are, however, serious impediments to salinity control through tree planting. Depending on the hydrogeological attributes of the catchment, this may involve the re-afforestation of large proportions of land (Lefroy and Stirzaker 1999; Hatton and Nulsen 1999). Also, tree crops may not be considered economically an attractive alternative by landholders. A disadvantage of growing trees as a farm enterprise is the long time lag between the investment associated with planting and the returns eventuating after harvest. Consequently, when evaluated with conventional discounting

[1] Engineering techniques include groundwater pumping, drainage channels and evaporation basins. These may be feasible for high value structures and urban water supplies.

techniques, farm forestry does not generally rank as an attractive alternative to crops on productive land (Schofield 1992).

The question then arises: under what conditions are tree crops profitable enough to provide a clear financial incentive for landholders to include them in their land-use system? This question has important social and economic dimensions and has implications for the efficient allocation of public resources between competing activities such as extension, research, subsidies and tax incentives. If farm forestry is a profitable alternative but has not been adopted because of lack of knowledge by producers, then education should be a priority. However, if the problem is one of low profitability of tree crops, then incentive instruments such as subsidies, tradable carbon credits and tax credits may be effective, complemented by funding of research aimed at producing higher yielding and/or faster growing trees for Australian conditions.

In this study we examine the conditions under which agroforestry would be an attractive alternative on cropping farms where dryland salinity is liable to emerge under conventional land use. A dynamic framework is adopted to capture the nature of resource problems, such as dryland salinisation, which are often characterised by time-dependent processes and causalities (Greiner 1996). The analysis is based on an optimal control model of a simplified agricultural production system involving four crops. For a series of prices, costs, yields, discount rates, initial land quality and credit availability, we investigate the optimal land-use system and level of salinity from a catchment-manager standpoint.

While most studies of dryland salinity have focused on a particular geographical area, we undertake an economic analysis of the problem at a more general level, by using a simplified model of the system, with what we view as the key components to achieve a realistic analysis. After a brief review of previous work, we present a general optimal control model containing an annual crop and a tree crop. We derive the first-order conditions for discounted profit maximisation over a limited planning horizon, discuss some difficulties in solving the model, and present a solution technique that involves a combination of simulation and nonlinear programming algorithms. We then develop a numerical model of the recharge area of a catchment and use the model to study alternative scenarios and policy measures. Although most parameter values are based on the Liverpool Plains of New South Wales, because it is a well-researched catchment affected by dryland salinity, we do not attempt to model a specific catchment but rather aim to draw some general conclusions.

2. Previous studies

Salinity has been a subject of economic analysis in Australia for nearly two decades. Theoretical aspects of the salinity problem were studied by Hodge

(1982), Quiggin (1986) and Gomboso and Hertzler (1991); these papers were followed by a number of applied studies, based on either simulation or mathematical programming.

Among studies at the farm level are those of Kubiki *et al.* (1993), Greiner (1994) and Mueller *et al.* (1999). Kubiki *et al.* (1993) developed a whole-farm simulation model (FARMULA) for the wheat belt in Western Australian and studied farm profitability and environmental degradation; they treated soil salinisation as an external variable. Greiner (1994) developed a dynamic whole-farm optimisation model (MoFEDS) for the Liverpool Plains in New South Wales, and explored best farm management strategies for farmers who face the threat of salinisation. Mueller *et al.* (1999) presented a dynamic optimal control model of salinity control at the farm level and studied the cost of switching between two land uses (cropping and native trees) and the optimal time for switching.

The literature also contains a number of studies at the regional or catchment scale. The studies by Salerian (1991) and Hertzler and Barton (1992) use a two-farm model to explore the effects of land use on salinity emergence and off-site costs in Western Australian catchments. Oram (1993) used a simulation model (SOILEC) that considers land management in the context of soil erosion, salinity, and farm income. The model has been used to demonstrate the beneficial effects of opportunity cropping and lucerne growing for recharge reduction. Greiner (1998) developed a catchment-level dynamic optimisation model (SMAC) which combines a fully-specified hydrological simulation model and an economic model. The model quantifies externalities and allows the analyst to establish socially optimal levels of salinisation and associated catchment management strategies.

This article falls somewhere between the applied and theoretical models reviewed above. The model we develop is detailed enough to capture the essential features of water-table dynamics, but simple enough to be used for detailed policy analysis under normative assumptions.

3. Dryland salinisation and groundwater table

Annual crops with shallow root systems, such as wheat and sorghum, and their requirement for extensive fallow periods, generate high recharge rates to the groundwater. Given the prevailing hydrogeological conditions in many catchments in southern Australia, this causes groundwater tables to rise. In the process, historic salts are mobilised and cause soil salinisation once a critical depth of groundwater table is exceeded. Crop growth, and hence farm profits, are negatively affected by salinity. Deep-rooted perennial crops have higher transpiration rates and, especially when tapping into a shallow aquifer, can cause groundwater levels[2] to decline. Because rising groundwater is the vehicle for mobilised salt, there is a strong correlation between depth of groundwater table and soil salinisation. There is an obvious trade-off between present and future profits when the crops that are more profitable in the short term are also the ones that contribute to salinity emergence in the longer term.

Our analysis is concerned with salinity management on the discharge area of a catchment. We are not concerned with the externality side of the problem as this has been considered elsewhere (Greiner 1996) and is also the subject of ongoing research. Rather, we attempt to understand the dynamic behaviour of salinisation under normative assumptions.

Conceptually, the direction and magnitude of change of groundwater level in a given year depend on three factors; the recharge balance generated by the given area of the catchment, the groundwater received from upstream parts of the catchment, and the amount of groundwater draining further downstream or out of the catchment. The decision variables in this system are the areas planted to individual crops. Depth of groundwater table is the key state variable; if it declines below a critical level, crop yields are reduced and may eventually reach zero.

As the extent of soil salinity and depth of groundwater table are correlated, the effects of salinity on growth (G_j) of crop j can be represented as a function of the depth of groundwater table (w). It is convenient to express G as a 'yield multiplier' with a value between zero and one. The value of G for crop j is represented by the equation:

$$G_j = 1 - \beta e^{-\varphi w}. \tag{1}$$

This functional form was selected because it is a plausible representation of the nonlinear process we seek to simulate (McLaughlin 1999, pers. comm.). The parameters β and φ can be algebraically related to the salinity levels assumed in the SMAC[3] model of Greiner (1998). In equation (1), when w is sufficiently large, yields are not affected by salinity and G_j has a value close to 1. If the depth of the groundwater table declines below a critical depth

[2] Groundwater 'level' is used as synonymous with 'groundwater table'. It is the absolute altitude of an aquifer in metres above sea level. 'Depth of groundwater table' is the difference in altitude between soil surface and groundwater level.

[3] SMAC stands for Spatial Optimisation Model for Analysing Catchment Management. The model was developed to investigate the relationship between land use, water tables and salinity at the catchment level. SMAC incorporates biophysical and economic aspects into a mathematical programming framework. The model contains four hydrogeological areas and a large number of cropping options.

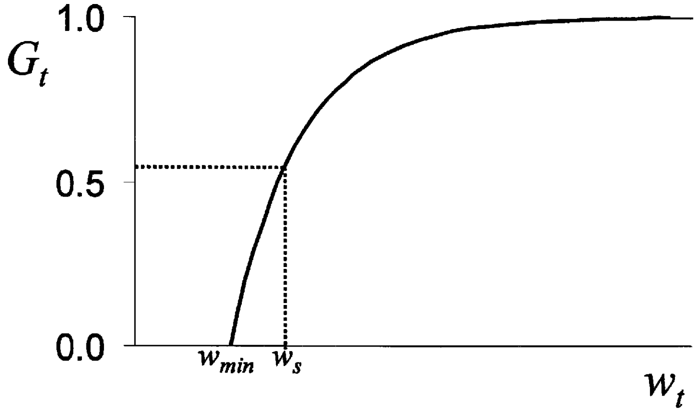

Figure 1 Effect of salinity on yields, equation (1)

(w_s), yields will be adversely affected (figure 1) and this effect will be increasingly severe until a point is reached (w_{min}) where crop j can no longer grow. Crop yields are consequently defined as:

$$Y_j = \overline{Y}_j \cdot G_j \tag{2}$$

where $\overline{Y}_j$ represents the expected yield of crop j in the absence of salinity and Y_j is the actual yield. The dynamic behaviour of the groundwater system is captured as a difference equation:

$$w_t = w_{t-1} + \Delta w_t \tag{3}$$

where:

$$\Delta w_t = \frac{-\mathbf{r_t} \cdot \mathbf{x}'_\mathbf{t}}{\theta \cdot L}. \tag{4}$$

Here, the numerator is the product of two vectors. Vector $\mathbf{r_t} = [R_{1t}, R_{2t}, \ldots, R_{kt}]$ contains recharge rate parameters associated with each crop. Vector $\mathbf{x_t} = [x_{1t}, x_{2t}, \ldots, x_{kt}]$ contains the area planted to each crop (hectares) during any given year t of the planning period. L is total area of land and θ is a coefficient that translates the farm's recharge balance into depth of groundwater table. We adopt the estimate provided by Greiner (1994) for this parameter, whereby 150 mm/m^2 mean annual recharge causes the soil pores of 1 metre of soil profile to be filled with water and therefore groundwater level to rise by 1 metre.[4]

[4] This assumes that the sum of the other two components of the water balance are equal: groundwater received from upstream parts of the catchment equals the amount of groundwater draining further downstream or out of the catchment.

In the field, actual recharge at a specific point in the landscape is not only a function of the crop but depends on a range of other factors including rainfall, land topography, soil type, and crop management practices. The purpose of our analysis does not require this level of detail. In our deterministic model we assume average rainfall conditions over the planning period and uniform land, soil and cropping practices across the discharge area of the catchment. Crop-specific recharge rates for annual crops are taken as constant and time-independent. Annual recharge rates of tree crops depend on their leaf-area index and are therefore age-dependent. Thus, the recharge rate associated with tree crop j is defined as:

$$R_j = \max\{\alpha_j + \gamma_j A_j, Rmin_j\} \tag{5}$$

where A_j is the crop age and $Rmin_j$ is the minimum level of recharge achieved[5] when trees reach maturity. The parameter α_j is the recharge rate associated with seedlings in the first year after planting. Parameter γ_j captures the increasing ability of trees to access and evapotranspirate soil and groundwater as they mature, thus $\gamma_j < 0$.

4. General model structure

A general optimal-control framework has been adopted to capture the dynamic relationships between land use and groundwater levels. Consider the problem of maximising the value of output obtained from an area L over a planning horizon of T years, subject to the dynamic behaviour of the groundwater table as affected by land use. Let the area planted to an annual crop and a farm forestry crop be denoted by x^a and x^f respectively. At any time there may be several stands of trees of different ages, depending on tree planting decisions in previous years. Let there be n age groups, or stands, the total farm forestry area at any time t is then:

$$x_t^f = \sum_{\tau=0}^{n} x_{\tau,t}^f \tag{6}$$

where τ represents the age of a stand of forest. The decision facing the land manager is the area of crop and forest to plant each year, as represented by the decision vector $\mathbf{u_t} = (x_t^a, x_{1,t}^f)$. The optimisation problem can now be defined as:

$$\max_{\mathbf{u_t}} V = \sum_{t=0}^{T} \left[x_t^a \cdot v_t^a(w_t) + \sum_{\tau=1}^{n} x_{\tau,t}^f \cdot v_{\tau,t}^f(w_t) \right] \cdot \delta^t + \delta^T F(w_T) \tag{7}$$

[5] The minimum recharge balance is negative (discharging) as trees transpirate more water than rainfall received.

subject to:

$$w_{t+1} - w_t = \frac{-\mathbf{r_t} \cdot \mathbf{x_t'}}{\theta \cdot L} \tag{8}$$

$$x^f_{\tau,t+1} - x^f_{\tau,t} = x^f_{\tau-1,t} - x^f_{\tau,t} \quad \text{for } \tau = 2, \ldots, n \tag{9}$$

$$x^a_t + x^f_t = L \tag{10}$$

$$x^a_t, x^f_{1,t} \geq 0 \tag{11}$$

$$w_0 = W \tag{12}$$

where the vector $\mathbf{x_t}$ is now defined as $(x^a_t, x^f_{1,t}, x^f_{2,t}, \ldots, x^f_{n,t})$ and $\delta = (1/(1+r))$ is the discount factor for the given rate r. The variable v^a is the return obtained from the annual crop net of variable costs (c^a), and $v^f_{\tau,t}$ is the return obtained from trees of age group τ net of establishment, maintenance and harvest costs (c^f_τ). Equation (9) is equivalent to the expression $x^f_{\tau,t+1} = x^f_{\tau-1,t}$ which simply transfers all trees from an age group into the next with no loss of trees. The form of equation (9) is used in an optimal control context for the derivation of the present-value Hamiltonian.

The return per hectare of crop and forest depends on the state variable w_t, which represents land quality as measured by depth of groundwater table, specifically:

$$v^a_t = \bar{y}^a G(w_t) p^a - c^a$$
$$v^f_{\tau,t} = \bar{y}^f_\tau G(w_t) p^f_\tau - c^f_\tau, \text{ for } \tau = 1, \ldots, n$$

where $G(w_t)$ is as defined in equation (1) and p^a and p^f are output prices. There are only two control variables in any one year, x^a_t and x^f_{1t}, as the remaining forest age groups are predetermined by planting decisions in previous years, as defined in equation (9). This is the key to the simplification undertaken to solve the numerical model explained later. The final value function, $\delta^T F(W_t)$, depends on the productivity of the land at the end of the planning horizon and its derivation is undertaken in a later section of the article.

The present-value Hamiltonian for this problem is:

$$\tilde{H}_t = x^a_t \cdot v^a(w_t) + \sum_{\tau=1}^{n} x^f_{\tau,t} \cdot v^f_\tau(w_t) + \delta\lambda_{t+1} \frac{-\mathbf{r_t} \cdot \mathbf{x_t'}}{\theta \cdot L} + \delta \sum_{\tau=2}^{n} \mu_{\tau,t+1} \left[x^f_{\tau-1,t} - x^f_{\tau,t} \right] \tag{13}$$

where λ_t and $\mu_{\tau,t}$ represent the costate variables (shadow prices) corresponding to the water-table and forest-area state variables respectively. Constraint (10) is introduced through the Lagrangean function

$$l_t = \tilde{H}_t + \eta\left(x_t^a + x_t^f - L\right) \quad (14)$$

The first-order conditions for maximisation are:

$$\frac{\partial l_t}{\partial x_t^a} \leq 0;\ x_t^a \geq 0;\ x_t^a \frac{\partial l_t}{\partial x_t^a} = 0 \quad (15a)$$

$$\frac{\partial l_t}{\partial x_{1,t}^f} \leq 0;\ x_{1,t}^f \geq 0;\ x_{1,t}^f \frac{\partial l_t}{\partial x_{1,t}^f} = 0 \quad (15b)$$

$$\frac{\partial l_t}{\partial \eta} \geq 0;\ \eta \geq 0;\ \eta \frac{\partial l_t}{\partial \eta} = 0 \quad (15c)$$

$$\delta\lambda_{t+1} - \lambda_t = -\frac{\partial \tilde{H}}{\partial w_t} \quad (16)$$

$$\delta\mu_{\tau,t+1} - \mu_{\tau,t} = -\frac{\partial \tilde{H}}{\partial x_{\tau,t}^f},\ \text{for } \tau = 2,\ldots,n \quad (17)$$

$$w_{t+1} - w_t = \frac{\partial \tilde{H}}{\partial(\delta\lambda_{t+1})} \quad (18)$$

$$x_{\tau,t+1}^f - x_{\tau,t}^f = \frac{\partial \tilde{H}_t}{\partial(\delta\mu_{\tau,t+1})},\ \text{for } \tau = 2,\ldots,n \quad (19)$$

$$\lambda_T = \frac{dF}{dw_T} \quad (20)$$

$$\mu_{\tau,T} = 0,\ \text{for } \tau = 2,\ldots,n. \quad (21)$$

The set of equations (15a, b and c) represents the maximum principle as modified by the Kuhn-Tucker conditions to satisfy constraints (10) and (11); equations (16) and (17) are the Hamilton equations for the costate variables; equations (18) and (19) are the equations of motion for the state variables; and equations (20) and (21) are the transversality conditions on the final value of the costate variables.

In theory, the solution to this problem can be achieved recursively, starting with the final value of the costate variables for a given final state $(w_T, \mathbf{x_T})$ and proceeding backwards in time solving equations (15) to (19). In practice, it is simpler to transform the model to a suitable form for numerical solution, using a gradient algorithm, rather than estimating derivatives numerically. These issues are discussed in Cacho (1998).

This model cannot be readily solved by dynamic programming (DP) because of the dimensionality of the resulting problem. The difficulty arises because, in addition to the state variable which is the focus of our study (w_t), we have $n-1$ additional state variables in the DP state matrix, namely $x^f_{2,t}, \ldots, x^f_{n,t}$. With $n = 35$ and a 40-year planning horizon, the resulting DP matrix would be unmanageably large.

Perhaps the most common approach to solving discrete optimal-control models consists of converting the problem to a mathematical programming form (Standiford and Howitt 1992). In this procedure the state and control variables in each time period are expressed as activities within a nonlinear programming (NLP) matrix, and the equations of motion are specified as non-linear constraints that link variables across time periods. The NLP approach can handle the dimensionality of the model better than DP, especially if costs and income occur only in a few years during the life of trees, which is likely to occur. However, the dimensionality of the problem is still an obstacle for two reasons. First, it may take several days to achieve convergence of the NLP on a conventional desktop computer and, second, it is likely that convergence will occur to a local maximum.

The solution approach we followed involved a combination of NLP and simulation. This was considered the most practical option because, although the solution of Δw_t, G_t and Y_t is computationally expensive in a mathematical programming sense, it is fairly straightforward in a simulation sense. These variables can be solved outside the NLP matrix, hence reducing the dimensionality of the problem considerably.[6] The disadvantage of the approach is that λ_t, the shadow price trajectory for w_t, is not obtained as part of the solution. However, the advantage of a manageable NLP model outweighs this shortcoming in the present study.

The model was implemented in a spreadsheet and solved with a commercial add-in package, What's Best! (Lindo Systems 1996). The time required to solve one run of the model was approximately 18 minutes. While the software uses a combination of nonlinear optimisation techniques in an attempt to avoid convergence to local maxima, there is no guarantee that the global maximum will be found. To reduce the likelihood of convergence to local maxima, the model was solved repeatedly for different initial states. In approximately 25 per cent of the runs a better solution was found by re-starting the model after convergence had been achieved. In our attempt to find global maxima we also resorted to a genetic algorithm (GA) e.g., see Goldberg (1989). A modified version of the model designed to run within a GA was allowed to run for several days, but was unable to improve on the NLP solution. This gave us some confidence that our solutions were 'optimal

[6] The senior author has discussed this approach with Greg Hertzler on several occasions and his contribution to the understanding of the technique is acknowledged.

enough' for the purpose of this study. Although GAs do not generally perform well in the presence of constraints on state variables, they still provide a convenient means of exhaustive search through the decision hypersurface.

5. The numerical model

The numerical model was designed to study the groundwater table dynamics under normative rules. The model abstracts away from some real-world complexities, such as spatial variability across the discharge area of the catchment, its links with other parts of the catchment and temporal variability associated with the stochastic nature of rainfall. However, by abstracting away from spatial differences and stochasticity, we hope to contribute to the understanding of processes that would be impossible to disentangle otherwise. The model is designed to explore the options available to a land manager in the discharge area of the catchment.

Four annual planting decisions were included in the model. A wheat-based rotation with short fallow (*Wht*) is the only annual crop system considered. Lucerne (*Luc*) is a semi-perennial crop with a four-year cycle. Eucalyptus woodlot (*EWL*) and eucalyptus oil (*EOil*) are the two farm-forestry options under consideration. The final or residual option is to let the ground lie fallow (*Fal*). This option does not affect returns but it does affect recharge rates and therefore has impacts on future productivity. In the model the fallow option is not treated as a decision variable, but it is accounted for by constraining any land area not planted to other crops to be categorised as fallow, with the corresponding recharge accounted for.

The numerical model is an extended version of that presented in equations (7) to (12), with x^a represented by *Wht* and x^f represented by *Luc*, *EWL* and *EOil*, with the corresponding modifications to the objective function and constraints. The land constraint (10) was set to 100 hectares for convenience; thus results represent hectares planted as well as percentages and can easily be extended to a different catchment area.

The original model was also extended by including a linear constraint on credit available per year:

$$\left[Wht \cdot c_{Wht} + \sum_{\tau=1}^{4} Luc_{\tau,t} \cdot c_{Luc,\tau} + \sum_{\tau=1}^{30} EWL_{\tau,t} \cdot c_{EWL,\tau} + \sum_{\tau=1}^{15} EOil_{\tau,t} \cdot c_{EOil,\tau} \right] \cdot (1+r) \leq K$$

The reason for the introduction of this constraint is to represent caution in the face of uncertain long-term investments such as *EWL* and *EOil*. The value of K was initially set at A\$30 000 per annum and, given the land-area

Table 1 Model assumptions and parameter values

Variable/ Parameter	Value	Description
L	100 ha	Land area
r	6 %	Discount rate
K	\$30 000	Credit limit per annum
w_0	4 m	Initial depth of groundwater table
w_{min}	0.5 m	Groundwater table depth for severe salinity
w_S	2.0 m	Groundwater table depth for moderate salinity
β	1.326	Salinity effect on yield parameter (eq. 1)
φ	0.564	Salinity effect on yield parameter (eq 1)
θ	150 mm/m^3	Recharge conversion factor (eq 4)
α_{EWL}	55.56 mm/m^2	Recharge parameter for EWL (eq. 5)
γ_{EWL}	−35.56 mm/m^{2}yr	Recharge parameter for EWL (eq. 5)
α_{EOil}	38.89 mm/m^2	Recharge parameter for EOil (eq 5)
γ_{EOil}	−18.89 mm/yr	Recharge parameter for EOil (eq 5)
$Rmin$	−300 mm/m^2	Minimum recharge for trees (eq. 5)

assumption, corresponds to a limit of A\$300 per hectare per year. This constraint may have important consequences which are explored in the results section.

Model parameters were based on coefficients used in the SMAC model (Greiner 1997, 1998). The parameters approximate those for black soil in the Liverpool Plains of NSW. Parameter values and other assumptions are presented in tables 1 and 2. Detailed simulation of actual rotations was not

Table 2 Crop parameters

Crop	Year	Yield	Price	Cost	Recharge
		(ton/ha)	(\$/ton)	(\$/ha)	(mm)
Wht	1	2.8	120	158	20
Luc	1	1	100	130	1
	2–4	4	100	180	0
EWL		(m^3/ha)	(\$/m^3)	(\$/ha)	(mm)*
	1			1920	20
	5			175	−122
	10	60	21	95	−300
	30	180	70	210	−300
EOil		(ton/ha)	(\$/ton)	(\$/ha)	(mm)*
	1			7367	20
	5–15	2.5	6000	10500	−56 to −244

Note: * Recharge rates for trees are estimated with equation (5) using parameters from table 1.

undertaken as it would have increased the complexity of the model unnecessarily given the objectives of this study.

The parameters of equation (1) were estimated algebraically (table 1). They are based on the assumption that the depth of groundwater table at which plants cease to grow (w_{min}) is 0.5 metres and that the critical depth for moderate salinity (w_s) occurs at 2 metres depth of groundwater table. The associated value $G(w_s)$ is 0.57. The same parameter values were used for all four enterprises. It is acknowledged that different crops may have different values of w_{min} and w_s, but in the absence of data and in the spirit of Occam's razor, we assume the same parameter values for all crops. The severity of this simplifying assumption is an empirical question and highlights an important research need.

Greiner (1997) estimated that in the establishment year, a eucalyptus woodlot in the Liverpool Plains generates recharge at a rate of 20 mm/m^2. By year five, the tree roots would be able to tap into a shallow groundwater table and the woodlot would transpire more water than it receives from rain, resulting in a discharging point water balance of -122 mm recharge per m^2. Water consumption of the tree crop would further increase up to maturity at age 20 with an associated recharge rate of -300 mm/m^2. Using this information, recharge parameters for tree enterprises were estimated algebraically based on equation (5). These parameters are presented in table 1 and assumed yields, prices and costs are presented in table 2.

The model was solved for a period of 40 years, resulting in a total of 160 decision variables. The model was solved in two stages. In the first stage, the terminal value of the land was ignored in the objective function — $F(w_T)$ was set equal to zero — and the model was solved for different initial levels of land quality (w_0). The optimal present value, V^*, obtained from each solution was taken as an approximation to land value in a perfectly competitive land market (e.g., Samuelson 1976; Comolli 1981). This information was used to estimate the function $F(w_T)$, which was then incorporated into the objective function. This second stage provided the complete numerical model used in analysing various scenarios.

The assumptions in the base scenario (scenario B) are summarised in tables 1 and 2. Table 3 describes the changes to parameters that constitute the other scenarios simulated. Scenarios A and C were designed to study the effect of initial land quality on catchment management required for economic efficiency. Scenarios D, E and F were designed to study, respectively, the effects of relaxing credit constraints, the effect of higher discount rates and the effect of higher recharge rates under annual crops.

The model was also run for various combinations of planting costs, timber prices and timber yields to gain insight into the possible consequences of subsidies and R&D on the optimal level of land quality at the catchment level.

Table 3 Scenarios

Scenario	Description	w_0	r	Recharge: Wheat	Recharge: Fallow	K
A	Poor land	2	0.06	20	40	30 000
B	Base case	4	0.06	20	40	30 000
C	Good land	8	0.06	20	40	30 000
D	High credit	4	0.06	20	40	100 000
E	High discount	4	0.10	20	40	30 000
F	High recharge	4	0.06	30	60	30 000

Table 4 Optimal results [a]

Scenario	V^* ($)	Average optimal annual value: w_t^* (m)	EWL^* (ha)	$EOil^*$ (ha)	Luc^* (ha)	Total perennials (ha)
A	159 484	8.44	23.30	2.19	13.77	39.25
B	225 881	7.54	15.14	2.19	7.98	25.31
C	285 257	7.72	5.28	2.35	0.00	7.64
D	272 863	10.28	18.35	13.63	13.80	45.78
E	102 239	4.54	6.98	0.00	9.07	16.05
F	222 195	7.52	15.84	2.35	16.00	33.81

Note: [a] Results present average values over 40 years.

6. Results

6.1 Scenario analysis

The model was solved for the six scenarios described in table 3 and the results are summarised in table 4. In the base case (scenario B), the average groundwater depth was 7.54 m below the soil surface. This was achieved by planting approximately 25 per cent of the land area to perennials (trees and lucerne). The main mechanism of groundwater control was planting *EWL;* 15 per cent of the area was planted to this enterprise (table 4). The effects of changes in the base assumptions on optimal management are discussed below.

6.2 Initial depth of groundwater table

An initial shallow depth of groundwater table (scenario A) causes the total area planted to perennials to increase to 39 ha (23.3 ha of *EWL*, 2.2 ha of *EOil* and 13.8 ha of *Luc*), a 55 per cent increase relative to the base case. By comparing the objective value V^* obtained under scenario A with that obtained in the base case (table 4), we see that, under optimal management, the cost, in present value terms, of a 2-metre difference in the initial depth of groundwater table is A$664 per hectare.

An initially large depth of groundwater table (scenario C) results in only 7.6 ha of perennials planted, a 70 per cent decrease with respect to the base case. Lucerne did not enter the optimal solution at high w_0 values (8 m), because there was no pressure for initial recharge control.

6.3 Credit

Increasing available credit to A$100 000 per year (scenario D) resulted in a dramatic increase in the amount of *EOil* planted, from 2.2 ha to 13.6 ha, more than a five-fold increase (table 4). This result is not surprising given the high initial investment required and the consequent effect of investment capital available on the establishment of this enterprise. There were also increases in areas of *Luc* and *EWL* planted, for a total increase in perennials of 80 per cent relative to the base case (from 25.3 ha to 45.8 ha). Consequently average w_t^* increased by almost 3 metres relative to the base case (from 7.5 m to 10.3 m). In present value terms, the increase in credit is worth A$470 per hectare (compare V^* values for scenarios B and D).

6.4 Interest rate

Increasing the discount rate from 6 to 10 per cent (scenario E), the average area planted to perennials decreased by 37 per cent, to a value of 16 ha (table 4). The major difference is that much less land was planted to trees, specifically *EWL*, reflecting a switch away from long-term investments in recharge control. Consequently, the average depth of groundwater decreased by 3 m (to 4.5 m). In present value terms, the increase in r by 4 percentage points costs A$1236 per hectare (compare V^* values for scenarios B and E).

6.5 Recharge rates of annual crops

Increasing the assumed recharge rates under wheat and fallow (scenario F) had little effect on the optimal water-table depth; the average w_t^* was 7.52 m compared to 7.54 m in the base case. This could be expected as the ratio between recharge rates of annual and perennial crops shifted only slightly. As seen later, the adjustment to high recharge rates consisted of a large increase in lucerne planted (to an annual average of 16 ha). This action, coupled with small increases in *EWL* and *EOil*, caused the total area of perennials to increase by 34 per cent relative to the base case (from 25.3 ha to 33.8 ha). In present value terms, the increase in recharge costs nearly A$37 per hectare (compare V^* values for scenarios B and F).

In all cases, the area not planted to perennials was planted to wheat, except for 20 ha in the first year of scenario A which were left fallow. In general, results show that wheat is the preferred enterprise but, in order to maintain its productivity, it is necessary to plant perennials.

6.6 Groundwater and land-use dynamics

The results presented above are averages over a 40-year period and do not provide information on the path of adjustment of groundwater table and land use through time. Figure 2 shows the optimal trajectory for the depth of groundwater table. Results are graphically expressed in terms of height ($-w_t^*$) because this is a convenient representation of what happens below ground level. Associated optimal land-use systems are depicted in figure 3. Under base assumptions (scenario B), w_t^* increases from an initial 4 m to 11 m by year 33 (figure 2A). The land-use responsible for this trajectory is planting 80 ha of lucerne in year 1 and planting trees during the first three years, to reach a total area of 20.2 ha of *EWL* by year 3 (figure 3 B). Lucerne gives early groundwater control while the trees become established. Between the tree harvest and final year, the depth decreases slightly to a final value of 10.3 m (figure 2A, line B). Interestingly, the optimal extent of forestry of about 20 per cent is equivalent to the socially optimal proportion of area planted to trees in the discharge area of the Liverpool Plains calculated by Greiner (1998) for a situation where trees did not generate a monetary return.

When the initial depth of groundwater table is 2 m (scenario A), the areas of lucerne and trees planted (figure 3A) are larger than in the base case, and this causes depth of groundwater to increase faster than in the base case

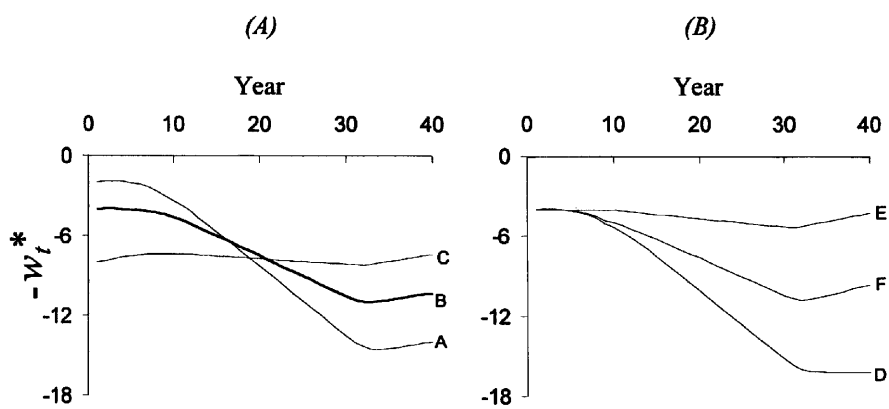

Figure 2 Optimal water table trajectories through time for six scenarios (A to F)

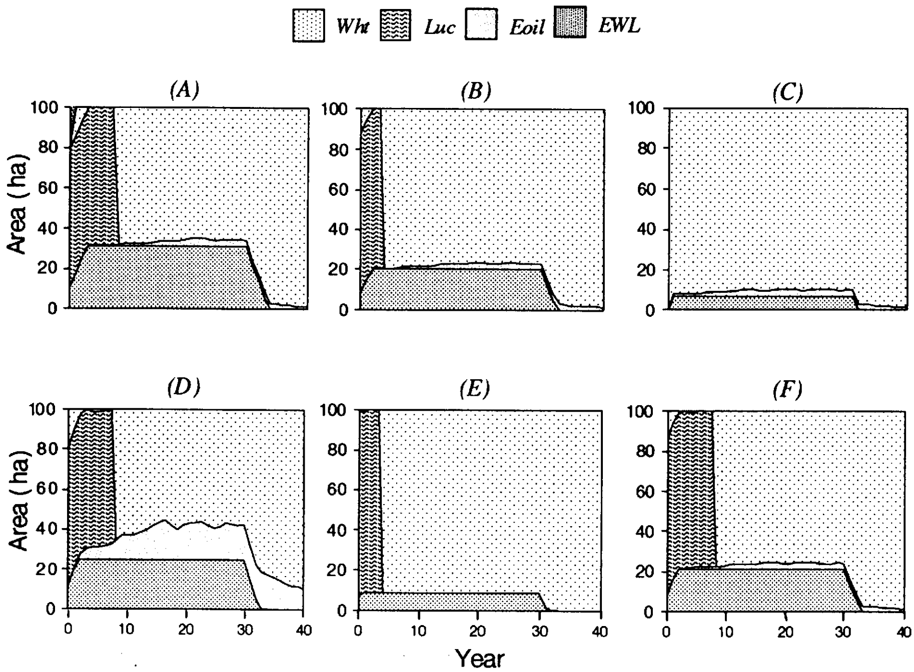

Figure 3 Optimal crop mix through time for six scenarios (A to F)

(figure 2A, line A). Thus, the requirement for immediate effective recharge control in the scenario with low initial land quality is reflected in the large proportion of land planted to lucerne (68 per cent) over the first eight years of the planning period. Also, by year 4, almost one-third of the land area has been planted to *EWL*.

In contrast, when w_0 is 8 m (scenario C), there is no immediate threat of salinity emergence. However, rather than continuing a cropping-only land-use regime, it is optimal to plant a small area of trees to maintain groundwater at a fairly stable level. Final depth of groundwater table is 7.4 m (figure 2A, line C). With high initial land quality (i.e. w_0 of 8 m), lucerne does not enter the optimal solution and the proportion of trees remains below 10 per cent of land area from year 3 to year 33 (figure 3 C). The area of *EOil* is small (around 2 ha) in all three scenarios A, B and C.

The economically efficient land status is highly sensitive to assumptions regarding credit limit and interest rates, as shown in scenarios D and E (figure 2B). Increasing the credit limit to A$100 000 per annum results in much larger areas of *EOil* planted in addition to *EWL* (figure 3D). Also, *Luc* replaces cropping for a period of almost 10 years. This causes the groundwater level to decline at a faster rate than in the base case, to a final depth of groundwater table of 16 m (figure 2B, line D).

Increasing the discount rate from 6 to 10 per cent (scenario E) leads to a significantly lower level of recharge control. *EWL* is below 10 per cent of land area and *Luc* is only grown for the initial five years (figure 3E). The final depth of groundwater table is 4.2 m (figure 2B, line E).

Assuming higher recharge rates under annual crops (scenario F) affects the optimal land quality status only slightly (compare lines B and F in figure 2). The system appears to adapt to the higher recharge rates by planting more *Luc* initially and increasing slightly the area planted to *EWL* (figure 3F) relative to the base case.

It appears that, under the assumed economic parameters, the optimal depth of groundwater table tends to a value of between 7 and 8 m — note the pattern in figure 2A. This suggests that, with a longer planning horizon, scenarios A, B and C would tend to converge to a common optimal depth of groundwater table. This hypothesis was tested by solving the model sequentially for five consecutive cycles, for a total of 200 years, resulting in an average w_t value of 7.6 m for the last two 40-year cycles (not shown). In summary, the long-term optimal depth of groundwater table (7.6 m) is well above the critical level (2 m) for emergence of salinity. This is consistent with the results obtained from both farm-level optimisation (Greiner 1996) and catchment-level optimisation (Greiner, 1998).

7. Policy analysis

Traditional policy measures to encourage individuals to adopt agroforestry to prevent salinity emergence include subsidies at planting and/or at harvest, research and development (R&D), farm extension and, more recently, social engineering through such institutions as Landcare and the media. Our model can only deal with the first two categories (subsidies and R&D) directly. However, the proper extension approach depends on whether the slow adoption of sustainable systems is caused by lack of information or low profitability; the model can thus produce useful information for the extension decision. Some other less traditional policies are also discussed in this section.

The likely cost of providing incentives that will achieve a given level of recharge and salinity control can be estimated by answering the question: what is the likely cost of a subsidy that causes average groundwater levels to decline by 1 metre? The question is answered by estimating elasticities with respect to planting cost and timber price (table 5). To this end, the model was solved with these variables set at 0.8, 1.0 and 1.2 times their base values in a 3×3 factorial design. Arc elasticities were calculated from the results.

The value of w_t^* is inelastic with respect to both planting cost (ranging between −0.91 and −0.39) and timber price (ranging from 0.35 to 0.86). Not surprisingly, the highest absolute elasticities of groundwater depth with

Table 5 Elasticities of w_t with respect to planting cost (ε_C) and timber price (ε_P)

Planting cost ($/ha)	Timber price ($/m^3) 56	70	84	ε_P
	Average w_t^* (m)			
1536	7.56	8.74	10.55	0.86
1920	6.88	7.54	8.59	0.57
2304	6.47	6.98	7.44	0.35
ε_C	−0.39	−0.58	−0.91	

respect to planting cost and timber price occurred at combinations of low costs and high prices. As we move from high-cost–low-price to low-cost–high-price combinations, the optimal watertable depth (w_t^*) increases from 6.5 m to 10.5 m.

Under base-case assumptions, a 1-metre increase in the depth of groundwater table represents a change of 1/7.54 or 13.3 per cent, and the corresponding elasticities are −0.58 and 0.57 for cost and price respectively (table 5). Thus, a 1 m increase in depth of groundwater table would cost A$439/ha to achieve through a planting-cost subsidy. At the expected timber yield of 180 m^3/ha, the cost of achieving the same result through a price subsidy at harvest would be A$2931/ha, which in present value terms is $359/ha, assuming harvest occurs in year 35. Extrapolating these results, if 20 per cent of the 15 million hectares of land estimated to be at risk from soil salinisation were to be planted to trees with the help of a subsidy, the cost to taxpayers would be A$1.08 billion and A$1.32 billion for price and cost subsidies respectively.

One way of increasing the appeal of farm forestry to landholders is R&D that results in earlier harvest, higher timber yields, and/or better quality timber. This can be achieved by developing better tree varieties through breeding and genetic engineering. To explore the effect of higher timber yields on possible adoption, elasticities were estimated by setting *EWL* yield at 0.8 and 1.2 times its base value and solving the optimisation model (table 6). The elasticity of w_t^* with respect to timber yield is 0.81. This means that, at base values, it would require a yield increase of 29.5 m^3/ha to achieve a 1-metre increase[7] in water-table depth.

[7] This assumes a base yield of 180 m^3/ha, so that an increase of 0.133 equals 23.9 m^3/ha; dividing this value by the elasticity (0.81) results in 29.5 m^3/ha.

Table 6 Effect of timber yields on optimal solution

		Average optimal annual value			
EWL Yield	V^* (\$)	w_t^* (m)	EWL^* (ha)	$EOil^*$ (ha)	Luc^* (ha)
Low	215 323	6.72	12.69	2.10	8.31
Base	225 881	7.54	15.14	2.19	7.98
High	239 254	9.17	21.30	2.30	0.00
Elasticity	0.26	0.81	1.42	0.23	−2.60

Our results suggest that, for the given assumptions and with perfect information, incentives should not be required to encourage adoption of farm forestry for recharge control, provided that the catchment is under the control of a single decision-maker or is managed as common property. Under base assumptions it is optimal to maintain the groundwater table at a depth that causes no salinity (7.3 m). These results, however, are based on a long-term perspective and a fairly low discount rate, assumptions consistent with social goals. Landholders may value inter-temporal trade-offs differently if they have shorter planning horizons and higher discount rates.

Chisholm (1992, p. 20) argues that off-site negative externalities 'would require a tax, not a subsidy, to equate marginal private and social costs'. But the answer may lie in a different direction. The low elasticities of groundwater depth with respect to price and cost subsidies suggest that we may want to revisit the ideas put forward by Quiggin (1986) regarding the management of groundwater as common property.[8] At the catchment level this would enable phasing in of farm-forestry rotations to be established across the catchment which, aggregated over all farms engaged in farm forestry, could guarantee a steady supply to a processing plant in the area, thus providing a local market for farm-forestry products and possibly encouraging adoption.

Quiggin (1986) proposes that property rights should be defined over assets (i.e., groundwater) rather than over activities (i.e., land clearing). He also points out that, while reassignment of rights between individuals is possible through voluntary exchange, the adoption of a new structure of rights requires unanimous consent 'since all holders of rights must voluntarily give them up' (ibid., p. 106). This may be very difficult to achieve, especially in large catchments. In the context of Quiggin's theoretical model, our model

[8] The term 'common property' is used in the correct sense, as opposed to open access. See Quiggin (1986).

contains the implicit assumption that the proportion of land in the discharge area (his parameter θ_i) is equal for all farms in the catchment. Quiggin shows that when spatial variability is introduced, a common property approach may not be sufficient to resolve unilateral externalities, and discretionary regulation may be required. Hodge (1982) and Quiggin (1986) propose an interesting system of marketable rights in cleared-land holdings (subject to the requirement that sensitive areas not be cleared) that could complement a regulatory regime.

Farm risk may also help explain slow adoption. The loss of an established forest to fire would be more damaging to the farm business than the odd loss of an annual crop, and mistrust regarding the stability of government policies may be an important deterrent. The scheme implemented by State Forests of New South Wales (SFNSW), whereby landholders receive a flow of annual payments in exchange for allowing part of their land to be planted to trees managed and harvested by SFNSW, may ease uncertainty and encourage adoption. Carbon credits may have a similar effect.

Recent concerns about global warming have led to proposals for the establishment of a carbon-credit system whereby owners of trees may be able to claim credit for the carbon dioxide absorbed by those trees. Trading systems may evolve which would allow credits to be bought and sold, thereby allowing growers to receive income from trees during their growth stage. There is considerable uncertainty about such trading systems and the values at which credits may trade. Depending on the level and nature of the payments, the credits may shift the optimal solution in favour of farm forestry. In the meantime, carbon credits have sparked intense interest in Australia, with small exchanges occurring between power companies and state forests. The Federal Government has sought advice from the Australian Greenhouse Office and a trial program is under way to deal with the establishment of a carbon-credit scheme.[9] A carbon-credit trading scheme may help prevent salinity emergence while also contributing to Australia's greenhouse gas commitments under the Kyoto Protocol. This is an important issue for future research.

8. Conclusion

The model developed here is a simplification of a highly complex land management and degradation system, but it contains the key features that assure its relevance to the problem under investigation. Assumptions are built on best available information with parameter values based on a well-researched catchment affected by salinity.

[9] A referee pointed this out.

The results obtained in the study suggest that, from an economic efficiency perspective, farm forestry may have an important role to play in the management of dryland salinity. As an enterprise, a woodlot is not very profitable but it has a strong impact on recharge control. It is this ability to lower groundwater tables and therefore maintain the productivity of adjoining cropping land that sees a woodlot implemented in the optimal solution on 5 to 23 per cent of land area depending on biophysical and economic assumptions.

The results of the study also indicate that subsidies on tree planting cost or timber harvest are not efficient policies, because of their high cost. A comprehensive policy approach towards salinity management through recharge control may need to include regulatory instruments that force landholders into participating in joint action. Without a regulatory component it may not be possible to achieve the overall scale of land-use change required to manage the salinity problem at the catchment level. However, there is still much room for debate on innovative policy packages which may be based on the view of groundwater as common property managed at the catchment level.

References

ABARE 1996, *Farm Survey Report 1996*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Cacho, O.J. 1998, 'Solving bioeconomic optimal control models numerically', in Gooday, J. (ed.), *Proceedings of the Bioeconomics Workshop*, 22 January, Armidale, NSW, ABARE, Canberra.

Chisholm, A.H. 1992, 'Australian agriculture: a sustainability story', *Australian Journal of Agricultural Economics*, vol 36, pp. 1–29.

Comolli, P.M. 1981, 'Principles and policy in forestry economics', *Bell Journal of Economics*, vol 12, pp. 300–5.

Davidson, S. 1993, 'Tree clearing in the semi-arid tropics', in Morris, B. (ed.), *Landcare – Science in Action*, CSIRO, East Melbourne, pp. 25–9.

Dryland Salinity Management Working Group, 1993, *Dryland Salinity Management in the Murray–Darling Basin. Stage 1 Report: The Dimension of the Problem*, prepared for the Murray–Darling Basin Ministerial Council, Murray–Darling Basin Commission, Canberra.

Farrington, P. and Salama, R.B. 1996, 'Controlling dryland salinity by planting trees in the best hydrogeological setting', *Land Degradation and Development*, vol. 7, pp. 183–204.

Goldberg, D.E. 1989, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley, New York.

Gomboso, J. and Hertzler, G. 1991, 'A hydrological-economic modelling approach to dryland salinity in Western Australia', paper presented at the Australian Agricultural Economics Society 35th Annual Conference, Armidale NSW, 11–14 February.

Greiner, R. 1994, *Economic Assessment of Dryland Salinity in the Liverpool Plains*, Department of Agricultural and Resource Economics, University of New England, Armidale, NSW.

Greiner, R. 1996, 'On-farm costs of soil salinisation', *Review of Marketing and Agricultural Economics*, vol. 64, pp. 60–74.

Greiner, R. 1997, 'Optimal farm management responses to emerging soil salinisation in a dryland catchment in Eastern Australia', *Land Degradation and Development*, vol. 8, pp. 71–93.

Greiner, R. 1998, 'Catchment management for dryland salinity control: model analysis for the Liverpool Plains in New South Wales', *Agricultural Systems,* vol. 56, pp. 225–51.

Hatton, T.J. and Nulsen, R.A. 1999, 'Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture', *Agroforestry Systems*, vol. 45, pp. 203–14.

Hertzler, G. and Barton, J. 1992, *Dynamic Model of Dryland Salinity Abatement*, Agricultural Economics Discussion Paper 4/92, University of Western Australia, Nedlands.

Hodge, I. 1982, 'Rights to cleared land and the control of dryland-seepage salinity', *Australian Journal of Agricultural Economics*, vol. 26, pp. 185–201.

Kennedy, J.O.S. 1986, *Dynamic Programming: Applications to Agriculture and Natural Resources*, Elsevier Applied Science Publishers, London.

Kubiki, A., Denby, C., Stevens, M., Haagensen, A. and Chatfield, J. 1993, 'Determining the long-term costs and benefits of alternative farm plans', in Hobbs, R.J. and Saunders, D.A. (eds), *Reintegrating Fragmented Landscapes: Towards Sustainable Production and Nature Conservation,* Springer-Verlag, New York. 245–78.

Lefroy, E.C. and Stirzaker, R.J. 1999, 'Agroforestry for water management in the cropping zone of southern Australia', *Agroforestry Systems*, vol. 45, pp. 277–302.

Lindo Systems Inc. 1996, *What's Best! User's Manual,* Lindo Systems Inc., Chicago.

Martin, L. and Metcalfe, J. 1998, *Assessing the Causes, Impacts, Costs and Management of Dryland Salinity*, Occasional Paper 20/98, LWRRDC, Canberra.

McLaughlin, D. 1999, Professor of water resource management, Massachusetts Institute of Technology, USA, personal communication.

Mueller, U., Schilizzi, S. and Tran, T. 1999, 'The dynamics of phase farming in dryland salinity abatement', *Australian Journal of Agricultural and Resource Economics*, vol. 43, pp. 51–67.

Murray–Darling Basin Ministerial Council 1999, *The Salinity Audit of the Murray–Darling Basin: A 100-year Perspective*, Murray–Darling Basin Commission, Canberra.

Oliver, M., Wilson, S., Gomboso, J. and Muller, T. 1996, *The Costs of Salinity to Government Agencies and Public Utilities in the Murray–Darling Basin,* ABARE Research Report 96.2, Australian Bureau of Agricultural and Resource Economics, Canberra.

Oram, D. 1993, 'Method for economic and financial impact assessment of dryland salinity control', in Murray–Darling Basin Ministerial Council (ed.), *Dryland Salinity Management in the Murray–Darling Basin*, Murray–Darling Basin Ministerial Council, Canberra, pp. 130–62.

Quiggin, J. 1986, 'Common property, private property and regulation: the case of dryland salinity', *Australian Journal of Agricultural Economics*, vol. 30, pp. 103–17.

Quiggin, J. 1987, 'Land degradation: behavioural causes', in Chisholm, A. and Dumsday, R. (eds), *Land Degradation: Problems and Policies*, Cambridge University Press, London.

Robertson, G. 1995, 'The National Dryland Salinity Program. Australian Bureau of Agricultural and Resource Economics', *Proceedings of the National Agricultural and Resources Outlook Conference 1995: Commodity Markets and Natural Resources*, ABARE, Canberra, pp. 213–20.

Salerian, J. 1991, 'Application of an economic model to dryland soil salinity in Western Australia', in *Proceedings of the International Economics Postgraduate Research Conference*, Economic Research Centre, Dept. of Economics, University of Western Australia, Nedlands, WA, pp. 97–108.

Samuelson, P.A. 1976, 'Economics of forestry in an evolving society', *Economic Inquiry*, vol. 14, pp. 409–92.

Schofield, N.J. 1992, 'Tree planting for dryland salinity control in Australia', *Agroforestry Systems*, vol. 20, pp. 1–23.

Standiford, R.B. and Howitt, R.E. 1992, 'Solving empirical bioeconomic models: a rangeland management application', *American Journal of Agricultural Economics,* vol. 74, pp. 421–33.

Stolte, W.J., McFarlane, D.J. and George, R.J. 1997, 'Flow systems, tree plantations, and salinisation in a Western Australian catchment', *Journal of Soil Research,* vol. 35, pp. 1213–29.